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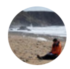

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Introduction

The Anthropocene: a new epoch of geological time?

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Anthropogenic changes to the Earth's climate, land, oceans and biosphere are now so great and so rapid that the concept of a new geological epoch defined by the action of humans, the Anthropocene, is widely and seriously debated. Questions of the scale, magnitude and significance of this environmental change, particularly in the context of the Earth's geological history, provide the basis for this Theme Issue. The Anthropocene, on current evidence, seems to show global change consistent with the suggestion that an epoch-scale boundary has been crossed within the last two centuries.

Keywords: Anthropocene; environmental change; human influence; geological time

1. Introduction

From the late nineteenth century, scientists were becoming aware of the extent of human influence on planet Earth. George Perkins Marsh's influential *Man and Nature* [1] is perhaps the first major work to focus on anthropogenic global change, while the Italian geologist Antonio Stoppani [2] coined the term 'Anthropozoic' to denote the time of this transformation. As the nineteenth century drew to a close, Svante Arrhenius [3] and Thomas Chamberlain [4] were exploring the relationship between CO_2 concentrations in the atmosphere and global warming. Arrhenius suggested that future generations of humans would need to raise surface temperatures to provide new areas of agricultural land and thus feed a growing population. In 2002, the Nobel Prize-winning atmospheric chemist Paul Crutzen [5] resurrected the concept of the Anthropocene to denote the current interval of time on Earth in which many key processes are dominated by human influence. The word quickly entered the scientific literature as a vivid expression of the degree of environmental change on Earth caused by humans, and is currently under discussion as a potential formal unit of the geological time scale [6,7].

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One contribution of 13 to a Theme Issue 'The Anthropocene: a new epoch of geological time?'.

2. What characterizes the Anthropocene?

The use of tools was once thought to distinguish humans from all other animals, and among the earliest people who lived at 2 Ma in Africa were *Homo habilis*, the 'handy man'. From that time, people have been modifying the Earth. For much of that human story, these changes were achieved by muscle and sinew, supplemented first by primitive tools, largely for hunting, and later by fire. Traces of humans in the Pleistocene rock record are rare, and stay rare until the Holocene.

The influence of humans is felt more strongly towards the end of the Pleistocene epoch, with the demise of much of the 'megafauna' that included the sabre-toothed cats in North America or the woolly mammoths of Siberia. On many continents, the disappearance of the megafauna appears to coincide with the arrival of modern humans. Like many events in the geological record, this extinction is diachronous—that is, happening in different places at different times. Thus, the megafauna disappeared in Australia 50 000 years ago, but in the Americas 13 000 years ago. Yet, the megafauna are still living in parts of Africa and South Asia, albeit under threat nearly everywhere.

From the beginning of the Holocene, about 11 500 years ago, evidence for human activities becomes more widespread, with the rise of agriculture beginning first in the 'fertile crescent' of the Middle East and gradually extending to northern Europe by 6000 years ago [8]. This change from hunting to cultivation leaves a clear fossil record in the pollen preserved in sedimentary successions through this interval. And, the clearance of forests, associated with the rise of agriculture, may have begun to elevate CO_2 levels in the atmosphere long before the Industrial Revolution [8].

Following the Neolithic revolution of agriculture, humans began to live in villages and towns, and by the third millennium BC the cities of ancient Mesopotamia, the Nile Valley and the Indus Basin of Pakistan were well established and culturally distinctive. Still later, urban cultures spread across the tropical and temperate zones everywhere, with those in Europe, Central and South America and China being diverse and advanced by the first millennium BC. This rate of urbanization has accelerated through time, with the first million-strong cities possibly appearing in late medieval times. By the nineteenth century, London and Paris had clearly reached this size. Now, there are many cities with between 10 and 20 million inhabitants. These are continuing to grow, rapidly.

Urbanization is a direct result of a population explosion. Since 1800, global population has risen from roughly 1 billion, to 6.5 billion in 2000 and a projected 9 billion by 2050. That population growth is linked with the Industrial Revolution, which supplied the power and technology to feed those extra mouths. Cities, and especially megacities like Jakarta, Rio de Janeiro or Shanghai, are now the most visible expression of human influence on the planet. The growth of cities is therefore a characteristic feature of the Anthropocene.

In 'terraforming' cities and building the dams and agricultural land that water and feed them, humans have wrought a roughly order of magnitude change in the long-term rate of erosion and sedimentation [9,10]. Paradoxically, while deforestation and changes in land use have resulted in more sediment transported in rivers, many of those rivers are now dammed, preventing the flow of that sediment to continental shelves [11]. Such changes may be impermanent. If human construction were to stop, for instance, nature would soon take over these constructions, reducing them to ruins over a matter of centuries. After a few millennia, perhaps only a patchy layer of concrete and building rubble would remain.

The biological and chemical signals left by humans—invisible, intangible in our day-to-day lives—may leave a signal more profound than the physical structures of the world's megacities. Thus, dissolution of increased atmospheric CO_2 into the oceans is increasing their acidity. A significant drop in oceanic pH has already occurred, and further decreases are almost certain. The biological response is complex, but will stress many calcifying organisms such as corals or the marine plankton that form the base of many food chains. Ocean acidification alone may substantially change marine ecosystems over the next century, contribute to global biodiversity decline, and so produce a distinctive event in the future fossil record.

3. Dealing with geological time

The Earth is over 4.5 Gyr old. This vast time span encompasses the formation of our planet and its oceans and continents, the origin of life and the evolution of the biosphere to its present complexity. To cope practically with such an extent of geological time, it is divided into more manageable packages that range from eons encompassing hundreds of millions—or indeed billions—of years, through smaller packages of time, such as the eras, typically characterized by a distinctive fossil record, perhaps most notably the dinosaurs and ammonites for the Mesozoic era beginning about 250 Ma and terminating some 66 Ma. These in turn are subdivided into periods of geological time, such as the Cambrian or Cretaceous, that may include distinctive, extensive rock units, such as the chalk strata of the latter. Periods are divided further into epochs and ages, and the record of fossils in rocks that were deposited in these shorter intervals of time is now so well constrained that we can correlate such units globally and reconstruct the appearance and conditions of our planet for many hundreds of different time slices.

The last period of time, the Quaternary, began just 2.6 Ma, and includes two epochs, the Pleistocene and the Holocene. The latter—by far the shortest in the geological time scale—began only about 11 500 years ago, witnessed by changes in climate that manifest in an ice core from Greenland [12]. The Holocene is really just the last of a series of interglacial climate phases that have punctuated the severe icehouse climate of the past 2 Myr. We distinguish it as an epoch for practical purposes, in that many of the surface bodies of sediment on which we live—the soils, river deposits, deltas, coastal plains and so on—were formed during this time.

4. Examining the Anthropocene

To the Quaternary period a third epoch might be added, the Anthropocene. Should it be formalized, and join the Carboniferous, the Jurassic, the Pleistocene and other such units on the geological time scale? This would be a major change to perhaps the most fundamental framework—the temporal one—used by Earth scientists. Such changes are not carried out lightly, and require wide discussion, consensus and agreement, under the aegis of the International Commission on Stratigraphy and the International Union of Geological Sciences. Are the changes involved in the Anthropocene of sufficient scale to warrant such formalization and—whether they are or not—is it useful to formalize the term in this way? Formalization would require precision of definition—and that would certainly help international and interdisciplinary communication. But excessive formality, of course, can act as a hindrance to working science. Where is the line to be drawn here?

This Theme Issue is a contribution to this debate, and was conceived to examine various aspects of the Anthropocene, and to stimulate debate, both about the term itself and (more importantly) about the phenomenon it encompasses: the transformation of the Earth's surface environments by human activity. This phenomenon is now arguably the most important question of our age—scientifically, socially and politically. We cannot think of a greater or more urgent challenge.

The opening paper of this issue by Steffen *et al.* [13] (the authorship including the architect of the term 'Anthropocene', Paul Crutzen) provides historical context to the Anthropocene concept, and examines the rapidly evolving—indeed, accelerating—trends in many global environmental signals, from resource use on land to patterns of oceanic and atmospheric chemistry. The authors stress recent human innovations—for instance, the startling advances in genomics that may profoundly impact on the future evolution of the biosphere. The effects of such transformational technologies may come to dwarf those of the smokestack industries, as regards lasting effects on this planet.

The Anthropocene is here treated as a geological phenomenon, comparable to some of the great events of the Earth's deep past. But, the driving force for the component global changes is firmly centred in human behaviour, particularly in social, political and economic spheres. The paper by Kellie-Smith & Cox [14] examines the relations between the financial markets and the Earth's environmental life support systems. They suggest that the future course of this relation may be influenced by a stabilizing negative feedback—thus, as environmental degradation hinders economic development, adverse affects on the markets will limit investment, acting as a brake on the likes of resource depletion and carbon emissions.

The science of Anthropocene change to the oceans is analysed by Tyrrell [15]. The major phenomena here are warming (and sea ice loss at high latitudes), sea-level rise and acidification, all demonstrably processes that are already initiated; and changes to ocean circulation, that have yet to be clearly demonstrated. Tyrrell shows how processes such as carbonate compensation will probably lead to continuing ocean change for many millennia into the future, even after anthropogenic CO_2 emissions cease.

Vidas [16] examines the history of the law of the sea, the framework that regulates humanity's exploitation of the vast (but finite) resource of the oceans. This framework stemmed from the early seventeenth century concept of *Mare Liberum*—'the freedom of the seas'—by Hugo Grotius (originally commissioned to justify what was, in effect, the life of the privateer). Subsequently shaped by national, territorial forces, this developed into the modern framework, where geological concepts (like the extent of the continental shelf) remain central to such matters as national claims to stretches of the sea. Now, Vidas argues, as the oceans themselves change through anthropogenic pressure, one must envision new principles that acknowledge those pressures, to underpin future iterations of the law of the sea. Tickell [17] reflects more widely on the societal economic and social trends that brought about humanity's current, pivotal situation—and on the kind of dynamics and institutional arrangements that may be needed to allow an Anthropocene epoch in which future generations can thrive.

Haywood *et al.* [18] analyse some of the ancient climates of Earth. They conclude that the relevance of studying ancient warm climates is not in the search for a direct analogue for twenty-first century global warming, but in the assessment and calculation of the response of global temperatures to increasing CO_2 concentrations in the longer term (over multiple centuries), and in the assessment of the abilities of climate and Earth system models to predict future climate.

Syvitski & Kettner [19] show that the impact of humans on sediment flux began some 3000 years ago within the Yellow River basin. This trend accelerated in the past 1000 years, and the sum of human activity through deforestation, agriculture, mining, transport, waterway 're-plumbing', coastal trawling and climate change has produced an effect equivalent to the level of a geological climate event, such as seen in the transition between the Pleistocene and the Holocene.

Merritts *et al.* [20] show that conceptual models linking channel condition and sediment yield exclusively with modern upland land use are incomplete for valleys impacted by mill dams. With no equivalent in the Holocene or Late Pleistocene sedimentary record, modern incised stream channel forms in the mid-Atlantic region of the USA represent a transient response to both base-level forcing and major changes in land use beginning centuries ago.

Ellis [21] considers the transformation of much of the terrestrial biosphere into anthropogenic biomes, or anthromes. He analyses the scale of this transformation by comparing the extent of change through different time slices of the Holocene. While human influence has been significant for more than 8000 years, it is only the last century that has seen a majority of the biosphere transformed into intensively used anthromes, and these are characterized by novel ecological processes, in increasingly profound manipulations of entire ecosystems.

Zalasiewicz *et al.* [22] consider contemporary environmental trends in stratigraphic terms, for instance, translating landscape modification (including urban growth) as a new lithostratigraphic signal, and biodiversity change as the fossil record of the future. Factoring in the potential for preservation of modern anthropogenic phenomena means that some of the most striking contemporary signals, such as megacity growth, may have low preservation potential, depending on tectonic setting. Conversely, biodiversity changes (including such novel aspects as unprecedented levels of global species transfer) have considerable permanence in determining the future course of biotic development.

The stratigraphic signal left by humans is continued by Price *et al.* [23], who discuss the gemorphological impact of humans on Earth. They note that in the past 200 years, humans in the UK alone have excavated and built up more than four times the volume of Ben Nevis, Britain's highest mountain. Vane *et al.* [24] continue this theme, identifying a range of pollutants preserved in the sediments of the River Clyde that provide a stratigraphical record of the rise of Glasgow, one of the world's first industrial cities.

It is clear that much work remains to be undertaken to understand the Anthropocene, even as its defining processes evolve. Considering the present in terms of the deep past, and vice versa, is difficult, because the methods of description and analysis of these two temporal realms are often greatly different. Nevertheless, it is important to try to put contemporary changes to the Earth, as clearly as possible, into a deep time context. This Theme Issue is intended as a step in that direction. The results of the studies herein, in sum, indicate that anthropogenic influence on Earth, albeit only briefly sustained (to date) on geological time scales, is likely to have significant and long-lasting consequences. The Anthropocene, on current evidence, seems to show global change consistent with the suggestion that an epoch-scale boundary has been crossed within the last two centuries.

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